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The Effects of Ionising Radiation on MEMS Silicon Strain Gauges: Preliminary Background and Methodology

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ABSTRACT

Despite limited reporting in the open literature describing the effects of ionising radiation on MicroElectroMechanical System (MEMS) devices or components, there are indications that some MEMS technologies exhibit vulnerability to radiation effects. To begin to gain an understanding of the issues surrounding the susceptibility of MEMS technologies, an investigation into the effects of radiation damage on the electronic and the mechanical properties of a specific MEMS silicon strain gauge will be conducted. The methodology followed is outlined in this report.

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Executive Summary

MicroElectroMechanical System (MEMS) technologies are driving the miniaturisation of mechanical components and the development of full system-on-a-chip devices. These technologies will fill an ever increasing demand for lighter, smarter components to be integrated into common equipment and the potential for the application of MEMS technologies within the ADF is extensive. As the scale of their components diminish, however, MEMS devices become potentially more sensitive to changes in their electrical and physical properties, such as those introduced by the damaging effects of ionising radiation. Prior knowledge of the radiation effects on MEMS devices and components is limited. However, there are some indications that particular MEMS technologies exhibit vulnerability to radiation effects. Therefore critical systems that may be required to operate within a radiation environment should be assessed for radiation-hardness. Operations within radiologically contaminated zones are one example, but operation at high altitudes also becomes significant due to the elevated ambient radiation background. The accumulation of radiation dose may impact on sensor equipment on aircraft designed for long flight hours, particularly for example UAVs designed for high-altitude long-endurance operations.

The principal objective of this research is to gain an understanding of the issues surrounding the susceptibility of MEMS technologies to ionising radiation, so that future systems can be assessed for potential problems. To achieve this, it is necessary to investigate the effects of ionising radiation on individual MEMS devices and/or common MEMS structures. A more immediate outcome can be simultaneously achieved by examining the susceptibility of current MEMS technology that is being developed for ADF use. Of particular interest are silicon strain gauges that use the response of piezoresistors to distortion as the sensing mechanism, which have been designed for structural health monitoring of vehicle panels, particularly air vehicles. From the literature it is anticipated that exposure to ionising radiation will produce a measurable change in the electronic output of the silicon strain gauges, but there are very few studies that examine the effect of radiation damage on the mechanical performance of single-crystal silicon. This investigation therefore has two primary objectives, to characterise the effects of radiation damage on the electronic output and to investigate the effects of radiation damage on the mechanical properties of the silicon strain gauges.

Two test methodologies to characterise the strain gauges have been developed; namely, direct control over the piezoresistor length changes, or application of strain by simulating device operation on a stressed substrate. Each of these methods has associated difficulties due to the particular design and extreme fragility of the silicon

strain gauges. Solutions for overcoming these difficulties are proposed and remain to be investigated before a complete electrical and mechanical characterisation of the silicon strain gauges may be reliably performed. The limited numbers of silicon strain gauges presently available places tight restrictions on the testing of these engineering solutions; work should not result in the destruction of many devices, or else insufficient numbers of gauges will remain for successful continuation with the next stages of the study. At present, there are just sufficient numbers to cover a complete investigation.

Following the electrical and mechanical characterisation, a series of irradiations will be undertaken. This will involve exposures to gamma-rays and neutrons within the HPPD Radiological Exposure Laboratory as well as proton exposures in an accelerator facility at the Australian Nuclear Science and Technology Organisation (ANSTO). Preliminary proton irradiations have been performed to define the methodology for the exposures in the ANSTO facility. This early work has demonstrated radiation effects, with the electrical resistance of the sensing elements changing almost linearly with proton fluence. These induced changes could potentially lead to errors in the determination of strain under conditions where the radiation exposure is not uniform over the entire device.

Of greater significance, however, is how the radiation affects the measurement of a true strain. The interpretation of the strain gauge output depends upon knowledge of the precise relationship between the true strain and the resistance changes of the sensing elements. It is quite possible that this relationship will be altered by radiation damage. This would result in an incorrect estimation of panel strain from the strain gauge output and the possibility that a fatigued panel is kept in service due to this incorrect reading. The extent to which the radiation damage alters this response as well as the fatigue lifetime of the strain gauges themselves remains to be determined.

The knowledge of the relationship between radiation damage and sensor output that will be obtained through completion of the radiation effects study could potentially lead to the development of novel radiation sensors. Exploiting the radiation effects on MEMS technologies could aid in the design of radiation detectors that are smaller and lighter than the current generation of detectors. The lower costs associated with mass-production of MEMS could also allow greater integration across the whole of ADF. Establishing the relationship between radiation damage and sensor output for the silicon strain gauges will allow the strain gauges to be assessed for this role and the physical principles determining the relationship can be assessed for application in new configurations to yield greater sensitivity or robustness.

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1. Introduction

Micro-Electro-Mechanical Systems (MEMS) devices are shaping up to be the next generation of sensor technology. Worldwide, they are already used in diverse applications, with devices to measure pressure, strain, corrosion and acceleration as the most common examples available in the commercial marketplace. MEMS technologies provide the ability to detect and measure a wide variety of physical properties with extreme sensitivity, such that devices under development can measure the mass of an object down to 10^{-18} grams [1] or inertial motion on the order of nanometres [2], for example. Most significantly, however, MEMS technologies are driving the miniaturisation of mechanical components and the development of full system-on-a-chip devices. These technologies will fill an ever increasing demand for lighter, smarter components to be integrated into common equipment.

The potential for the application of MEMS technologies within the ADF is extensive. Applications may include specific micro-scale devices, such as distributed battlefield sensor networks for situational awareness or biomedical devices, or the application of miniaturised electronics in areas such as UAV communications and control systems, to mention just a few examples [3],[4]. Within DSTO, MEMS technology is presently being investigated in areas such as RF detection, tuneable radar, structural health monitoring (corrosion and strain sensing) and power production.

2. Ionising Radiation Susceptibility of MEMS

As the scale of their components diminish, devices become potentially more sensitive to changes in their electrical and physical properties. The macro-scale material behaviour may not necessarily translate to the micro-scale MEMS components [5]. Unwanted or unexpected changes could potentially lead to performance degradation or complete system failure.

Some of these undesirable effects can be introduced by exposure to ionising radiation. Ionising radiation passing through matter transfers its energy to the material through a variety of interaction mechanisms. The two foremost consequences of this energy deposition are ionisation and atomic displacement, each of which may be responsible for degradation effects in devices, depending on the physical principles on which the device operates.

Ionisation is the creation of free charges within the material through the creation of electron-hole pairs. This can result in effects such as transient current pulses or an accumulation of trapped charge in dielectric components, for example. This latter effect is significant in some insulating, dielectric materials such as the silicon dioxide layers commonly used in integrated circuits and MEMS components [6].

A proportion of the energy transferred by the passage of ionising radiation is deposited through non-ionising interaction losses that lead to atomic displacements. In this process, energy is transferred to kinetic energy of the atomic nuclei of the material. The nuclei are displaced from their stable positions, distorting the lattice structure of a material and creating structural defects. This can affect a material's electronic properties (especially in the case of semiconductors, discussed below in Section 6) or its mechanical properties, such as the reductions in ductility and fatigue life demonstrated in stainless steels due to neutron irradiation [7]. The proportion of energy that goes into creating atomic displacements depends on the radiation type and the target material, but is generally low for photons (gamma and x-rays), moderate for protons and highest for neutrons [6].

Limited literature exists on radiation effects in MEMS devices or components. The proprietary nature of most MEMS devices complicates the open literature reporting, and many studies are simply not published [8]. The majority of previous work has demonstrated radiation effects on the activation of mechanical elements related to charge build-up in the dielectric or insulating layers. These charge build-up effects have been demonstrated in MEMS accelerometers [9], optical mirrors [10] and RF relays and switches [11], and are dependent on the design geometry and actuator materials of the devices. A recent study of MEMS pressure transducers and accelerometers utilising piezoresistive elements has shown changes in sensor output due to high gamma radiation exposures [12]. Most significantly, this study demonstrated that the effects were more pronounced as the dimensions of the piezoresistive elements were reduced. This study will be discussed in further detail in Section 6, below. Thus, despite the paucity of reports, there are indications that some MEMS technologies exhibit vulnerability to radiation effects.

3. Radiological Concerns

Operations in a radiologically-contaminated environment, either as a result of nuclear weapons use, radiation dispersal devices or nuclear accident, will require systems to handle elevated dose rates and/or high accumulated doses. MEMS devices exposed to this environment would principally be devices integrated into future electronics systems such as communications equipment or sensor systems on land platforms (e.g. advanced NBC reconnaissance vehicles) or incorporated into standard issue equipment used by teams operating in a contaminated environment, for example. Critical systems that could potentially be required to operate within a contaminated environment, whether or not designed primarily for the purpose, should be assessed for radiation-hardness.

There is also a constant background of ionising radiation present, from natural radioactivity in the environment as well as from cosmic sources such as the Sun. At the surface of the Earth this ambient radiation background is not significant, causing very few radiation problems. In particular, the contribution from cosmic radiation at ground level is very minor because of the shielding provided by the intervening atmosphere. At high

altitudes, however, cosmic radiation becomes significant as there is less atmospheric shielding and consequently a higher ambient radiation background.

B. J. Lewis *et al.* [13] provide a comprehensive description of the cosmic radiation environment. Within the atmosphere, particularly at aircraft altitudes, the major contribution to the radiation background comes from secondary radiations, such as neutrons and protons, created by the interactions in the atmosphere of the high energy cosmic rays. The dose rate from these secondary neutrons and protons generally increases with altitude, peaking at around 20 km (~ 60 000 ft) above sea-level. The dose rate due to the cosmic radiation background depends not only on altitude, but also on the geomagnetic latitude and on the solar cycle. The Earth's magnetic field screens much of the incident cosmic rays and this shielding is greatest for particles entering at the equator, where they come in at right angles to the magnetic field, but is less effective at higher latitudes. In addition, solar flare events can have a particularly significant contribution to the dose rate, but are comparatively short-lived events.

The complex spectrum of radiation types and energies, as well as the variations according to height, latitude, etc. make it difficult to estimate average dose rates experienced by different air platforms. Various studies have been performed to characterise the atmospheric radiation environment for the calculation of flight crew exposures and the effects on avionics [13] – [15]. For the purposes of this study maximum dose rates up to ~10 $\mu Sv.h^{-1}$ at 40 000 ft and ~ 25 $\mu Sv.h^{-1}$ at 60 000 ft [13] – [16] will be considered.

As such, the instantaneous dose rate from cosmic radiation is not generally sufficiently high to cause immediate or short term problems. For example, a passenger in a single flight from Sydney to Perth at jet altitudes will be exposed to a maximum total dose of 50 μSv from cosmic radiation, which is one-fortieth of the average dose accumulated from all background sources in a year by the average person, and which does not pose any significant health hazard.

Cosmic radiation becomes an issue as the total accumulated dose increases with the length of time spent at high altitudes. This may impact on sensor equipment on aircraft designed for long flight hours, particularly UAVs designed for high-altitude long-endurance, as for example those being considered in Project AIR 7000 [17]. Total accumulated dose will also be high when viewed over the lifetime of an aircraft. Any components carried onboard these platforms will therefore be at risk from radiation damage as a result of the accumulated dose effects. For similar reasons the effects of cosmic radiation on standard commercial avionics have been the subject of many studies over the past decade, leading to the implementation of specific strategies such as error detection and correction to avoid systems failures associated with the radiation effects [14], [18].

4. Research Objectives

The principal objective of this research is to gain an understanding of the issues surrounding the susceptibility of MEMS technologies to ionising radiation, so that future systems can be assessed for potential problems. Knowledge gained may also be utilised in the design phase for critical MEMS systems, to avoid known susceptibilities before the systems are acquired. To achieve this, it is necessary to investigate the effects of ionising radiation on individual MEMS devices and/or common MEMS structures.

A consequence of uncovering a significant relationship between radiation damage and MEMS sensor output or behaviour could potentially be the development of novel radiation sensors. Exploiting the radiation effects on MEMS technologies could result in the design of radiation detectors that are smaller and lighter than the current generation of detectors. These could then be incorporated on a wider range of platforms, or allow greater flexibility in their use where an individual is typically encumbered by the weight and size of the current detectors. The lower costs associated with mass-production of MEMS could also allow greater integration across the whole of ADF, allowing, for example, integration into all combat uniforms.

A more immediate outcome can be simultaneously achieved by examining the susceptibility of current MEMS technology that is being developed for ADF use. Of particular interest to the Nuclear & Radiological Group are a series of silicon strain gauges (SiSG) developed by the MEMS Group within the Maritime Platforms Division. These strain gauges, developed under Task LRR 02/130 and LRR 99/061, have been designed to monitor the structural integrity of vehicle panels, in particular aircraft panels. It is intended that the devices will be permanently incorporated into the aircraft panels and so should have a useable lifetime greater than that expected of the aircraft. However, over a lifetime of 20 to 30 years, with many thousands of hours of flight time, the strain gauges will accumulate a significant dose of ionising radiation due to the increased ambient radiation at high altitudes.

5. Silicon Strain Gauges

The strain gauges utilise the piezoresistive properties of semiconducting silicon as the sensitive element to measure the degree of strain on a structure. Figure 1 illustrates the design of the SiSGs. The entire structure is manufactured from 100-μm-thick single-crystal silicon, etched via the deep-reactive-ion-etching process into ~ 100-μm-wide tracks. The main bulk of the device holds the contact pads for electrical connection between the piezoresistors and the measurement circuit. The strain gauge structure is attached to this silicon bulk by four 50-μm-wide tracks, which also carry the contact tracks between the pads and the piezoresistors.

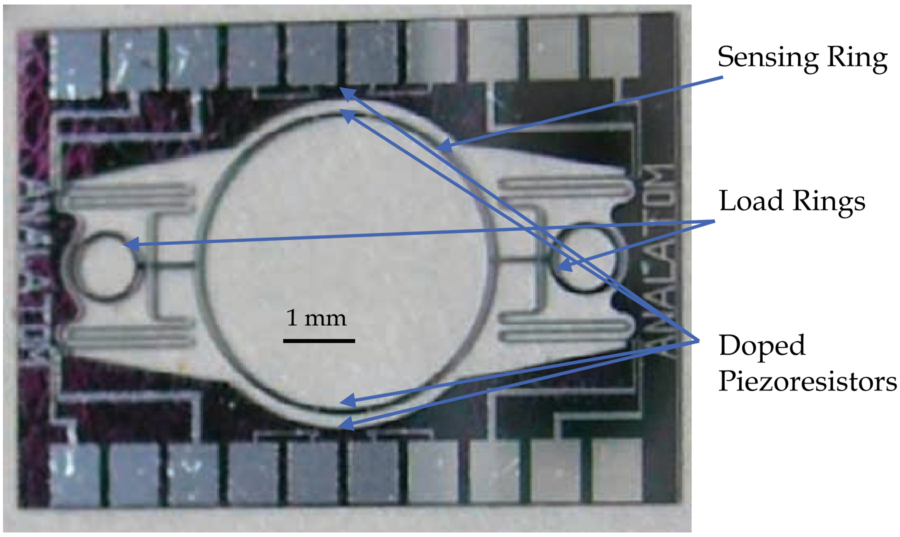

Figure 1: *Silicon Strain Gauge construction*

The sensing elements are p-type resistors, doped directly into the central 0.5-cm-diameter ring structure using Boron ion implantation. Each resistor is approximately 900 μm long and 15 μm wide. There are eight such piezoresistors doped into the silicon of each strain gauge; a pair on either side of the central sensing ring, such that one piezoresistor is doped along the inner edge of the ring and the second along the outer edge, and a further two pairs on the silicon bulk directly opposite those on the sensing ring. The resistors doped onto the fixed silicon bulk are not affected by strain, but act as temperature compensation references.

On either end of the central ring, at 90° from the piezoresistors, a neck leads to a load ring with a radius of 0.5 mm, designed to be the only point held fixed onto the material under test. The overall length between centres of the load rings at zero strain is approximately 7.8 mm. An older design, using a square-shaped load point, was also manufactured. These gauges, however, have only one or two piezoresistors that can be measured, due to processing problems with the metal-semiconductor contacts. Reference will be made to 'square-headed' and 'round-headed' SiSGs for the older and newer designs, respectively.

When an applied force deforms the material under test, the resulting deformation is translated to the strain gauge through the displacement of the load points. This in turn results in deformation of the central ring structure, and hence an elongation or compression of the piezoresistors that produces a change in electrical resistance. For p-type doped resistors, an elongation (positive strain) leads to a positive increase in resistance. The ratio of the fractional change in electrical resistance $\Delta R/R$ to the fractional change in length $\Delta l/l$ is related by the gauge factor (GF) of a strain gauge:

$$GF = \frac{\Delta R/R}{\Delta l/l} = \frac{\Delta R/R}{\varepsilon},$$

where $\varepsilon = \Delta l/l$ is the definition of strain.

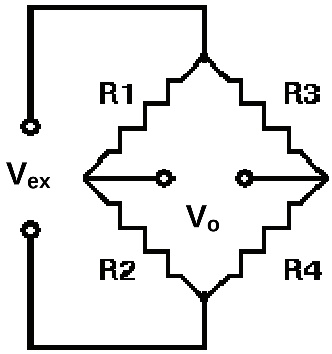

Figure 2: *Wheatstone bridge circuit arrangement*

To accurately measure the small changes in resistance, the four piezoresistors are connected into a Wheatstone bridge circuit, (Fig. 2). In a general Wheatstone bridge, the output voltage of the bridge, V_o, will be equal to

$$V_o = \left[\frac{R_4}{R_3 + R_4} - \frac{R_2}{R_2 + R_1} \right] \cdot V_{ex} ,$$

where V_{ex} is the excitation voltage applied to the bridge and R_1 to R_4 are the resistance values. If $R_1/R_2 = R_3/R_4$ when no strain is applied, then the voltage output is zero and the bridge is said to be balanced. A change in resistance is then measured as a shift in V_o.

The physical arrangement of the SiSG piezoresistors has been designed so that under compressive distortion of the sensing ring the two innermost resistors will compress while the outermost resistors will elongate (and vice-versa under tension). This behaviour results in equal but opposed resistance changes, ΔR, of the two pairs of piezoresistors and the voltage output can then be expressed as

$$\frac{V_o}{V_{ex}} = -\frac{\Delta R}{R} = -GF \cdot \varepsilon .$$

With a 10 V excitation voltage, for example, a 0.1% change in resistance could be measured as a 10 mV shift in output voltage. Therefore, when connected in this manner and using appropriate amplification of the output voltage, it is possible to measure small distortions in the ring structure that are caused by tensile or compressive forces.

The fine construction of the SiSGs makes them extremely fragile if incorrectly handled. The SiSGs have been designed to move with relative freedom along the principle axis running through the load points. Movement perpendicular to this axis but still within the plane of the gauge is compensated by flexing of the contact tracks leading from the load points to the silicon bulk, but this motion is restricted. Perpendicular to the plane of the gauge, on the other hand, movement can easily result in destruction of the fine silicon tracks. In operational use, the SiSGs will be packaged to provide more physical robustness,

particularly from motion perpendicular to the gauge plane. Incorporation into the panel structure will also add to the robustness. However, any packaging of the gauges under test would interfere with the irradiation studies, so the SiSGs require delicate handling during characterisation, as discussed below in Section 7.

6. Radiation Effects on Silicon Strain Gauges

Of primary concern in the silicon strain gauges are the effects of atomic displacement damage resulting from non-ionising interaction losses (see Section 2). Within semiconductor materials this displacement damage affects the electronic energy states, which can give rise to several processes, including increased thermal generation of electron-hole pairs, altered recombination of electron-hole pairs, trapping of charge carriers or compensation of donor or acceptor levels, for example [19]. The overall effect is to alter the conduction properties, such as carrier lifetime (affecting conductivity) and diffusion length (affecting the size of the depletion layer between semiconductor regions). The atomic displacement damage thus affects the semiconducting and piezoresistive properties of silicon.

As mentioned in Section 2, a recent study by Holbert *et al.* demonstrated some effects of high gamma doses on the piezoresistive properties of silicon [12]. The study examined MEMS accelerometers and pressure transducers constructed of p-type doped silicon piezoresistors, proposed for use in a nuclear reactor environment. An increase in the resistance of the piezoresistive elements was observed, attributed in the report to a growth in the depletion region surrounding the piezoresistors that results in an effective reduction in the cross-sectional area for current flow, thus increasing its resistance. It was also observed that this effect was greatest for the piezoresistive elements with the smallest dimensions, and hence smallest cross-sectional area. Changes in the dynamic response of the devices were also observed, however the authors did not ascertain what physical mechanism was involved.

Studies on non-MEMS piezoresistive elements have also demonstrated some degree of radiation effects, particularly increases in the resistance values [20]. It can therefore be anticipated that exposure to ionising radiation will produce a measurable change in the individual piezoresistors of the silicon strain gauges. However, the geometry of the strain gauge (Fig. 1) and the electronics used in the configuration in Figure 2 will reduce this effect since all the piezoresistor resistances will change by approximately the same amount in a uniform radiation field. The critical parameter to consider is thus whether the gauge factor, $(\Delta R/R)/(\Delta l/l)$, changes with radiation exposure.

What is not well understood, however, is how ionising radiation affects the mechanical performance of single-crystal silicon. The susceptibility of single-crystal silicon MEMS structures to crack growth has been demonstrated [21]. As such, the lifetime of the SiSGs may be limited by fatigue of the structural components of the gauges. However, there are

very few studies that examine the effect of radiation damage on fracture or fatigue life. A report by Wells *et al.* [22] observes changes in the mechanical properties of 2-μm-thick silicon nitride membranes due to x-ray exposures, showing a significant decrease in the elastic modulus, but there is little related to the effects in single-crystal silicon.

This investigation therefore has two primary objectives:

1. Characterise the effects of radiation damage on the electronic output of the silicon strain gauges
2. Investigate the effects of radiation damage on the mechanical properties of the silicon strain gauges

7. Methodology

7.1 Characterisation

To accomplish these aims, the mechanical properties and electronic response of the SiSGs must first be characterised in the absence of radiation damage. The principal measurement characterising the silicon strain gauges is the voltage output of the Wheatstone bridge arrangement when the device is subjected to a varying strain. From this, the SiSG's gauge factor can be calculated. Alternatively, the fractional change in resistance of each individual piezoresistor can also be directly measured.

Connection to the SiSG piezoresistors is achieved by mounting the devices on a flexible circuit carrier. The SiSG contact pads are connected to the flexi-circuit by a conducting adhesive. Electrical connection is then possible via an adaptor to a DB-25 connector.

Resistances are measured on a Keithley 2000 Digital Multimeter using a two-wire Ohm-sense arrangement. The data storage function of the Keithley was used to store 100 counts, with the average resistance and standard deviation calculated from the counts recorded. Measured resistances on all SiSGs average around 7 to 10 kΩ, with a spread of resistances on a single device typically around 500 Ω, and standard deviations typically < 100 mΩ. A few SiSGs were found to have a single resistor with a large resistance of ~ 25 kΩ; it is uncertain whether this is due to a difference in doping or a problem with the metal-semiconductor contacts. As mentioned previously, the older style square-headed SiSGs have known contact problems, so that typically only one of the piezoresistors on the central sensing ring can be measured, the remainder showing MΩ resistances or no connection at all.

Control of the distortion of the sensing elements can be achieved by either of two methods:

1. directly controlling the fractional length change $\Delta l/l$ of the piezoresistors by directly manipulating the displacement of the load points using an appropriate system, or
2. by applying strain to a substrate on which the devices are mounted.

7.1.1 Direct Displacement

A customised testing rig for direct control of the load point displacement, the 'Micro-Displacement Rig', was designed and constructed specifically around the round-headed devices, to within tight tolerances (Fig. 3) [23]. The SiSG is mounted onto two pins that sit within the load rings of the strain gauge. Each pin has been fixed onto separate arms, one of which can be moved to lengthen or shorten the distance between the pins. A micrometer allows fine movement of the arm, with a digital indicator providing a visual reading of the displacement. The pivot of the arms has been designed so that movement at the pins is one-tenth of the movement at the micrometer. This configuration allows fine control over $\Delta l/l$.

As the SiSGs are extremely fragile, removal of a mounted gauge from the rig proved to be extremely difficult. When lifting a gauge, any slight catch between the load ring and the pin can produce a force on the fine silicon structure perpendicular to the plane of the structure. In an early trial of the Micro-Displacement Rig, this led to the complete destruction of a strain gauge. A proposed solution to this problem is to modify the rig so that the pins may be retracted before the SiSG is lifted. This modification remains to be implemented and tested.

Preliminary measurements made on the Micro-Displacement Rig of the change in resistance value as a function of load-ring displacement on a single SiSG piezoresistor are

Figure 3: *Micro-Displacement Rig designed for manual characterisation of Silicon Strain Gauges.*

plotted in Figure 4a (page 11). A degree of hysteresis between the increasing Δl (upper) and decreasing Δl (lower) branches is evident in the figure. Factors contributing to this hysteresis may include the elastic response of the silicon ring structure or aspects of the engineering of the Rig. At temperatures below 500°C defect-free single-crystal silicon has been shown to be perfectly elastic [24] and is thus expected to have almost zero hysteresis. Further investigation will therefore be required to discover to what extent the hysteresis results from the design of the strain gauge, as opposed to the construction of the Micro-Displacement Rig.

When the data of Figure 4a is represented as fractional changes (Fig. 4b), an almost linear relation between $\Delta R/R$ and $\Delta l/l$ is observed. The ratio between the fractional changes defines the gauge factor, *GF*, of the strain gauge. However, for the silicon strain gauges, the measured change in length is that between the load points, and not the change in length of the piezoresistors themselves, so the above relation does not hold exactly. It can be assumed that over the small displacements involved the fractional change in length of the piezoresistors is linearly related to that between the load points. With this assumption, a generalised gauge factor can be calculated that reflects the strain gauge performance, $GF \approx 2$ (averaged between both arms).

7.1.2 Substrate Mounted

To simulate operation of the devices as strain gauges, the SiSGs are mounted on a test structure called a 'dogbone'. A cycle of tensile and compressive loads are applied to the dogbone, which is designed to transmit the stresses onto the strain gauge. In addition to measuring the effect of radiation on the electrical properties, the effect on mechanical properties can also be determined, using cyclic fatigue testing [7]. This test *requires* the strain gauges to be mounted on a dogbone.

In mounting the SiSGs onto a substrate, only the load points should be firmly affixed, leaving the remainder of the gauge structure free to flex. Mounting of the strain gauges therefore involves the application of an adhesive into the load rings of the strain gauges. This requires precise dispensing of an appropriate adhesive. An air-exhaust dispenser was initially chosen that allows control over the air pressure and timing used to dispense the adhesive, thereby controlling the volume of adhesive dispensed. The dispensing technique, however, is complicated by the small size of droplet required; the viscosity of the adhesive can impair the formation and dispensing of a sufficiently small droplet. The solution arrived at was to use the dispenser as a form of stamping tool. That is, the droplet is formed on the tip of the dispenser while in contact with the dogbone, and the tip is then withdrawn vertically, leaving the adhesive within the load ring. Any horizontal movement will move the strain gauge and/or smear adhesive outside the load ring, both of which are to be avoided.

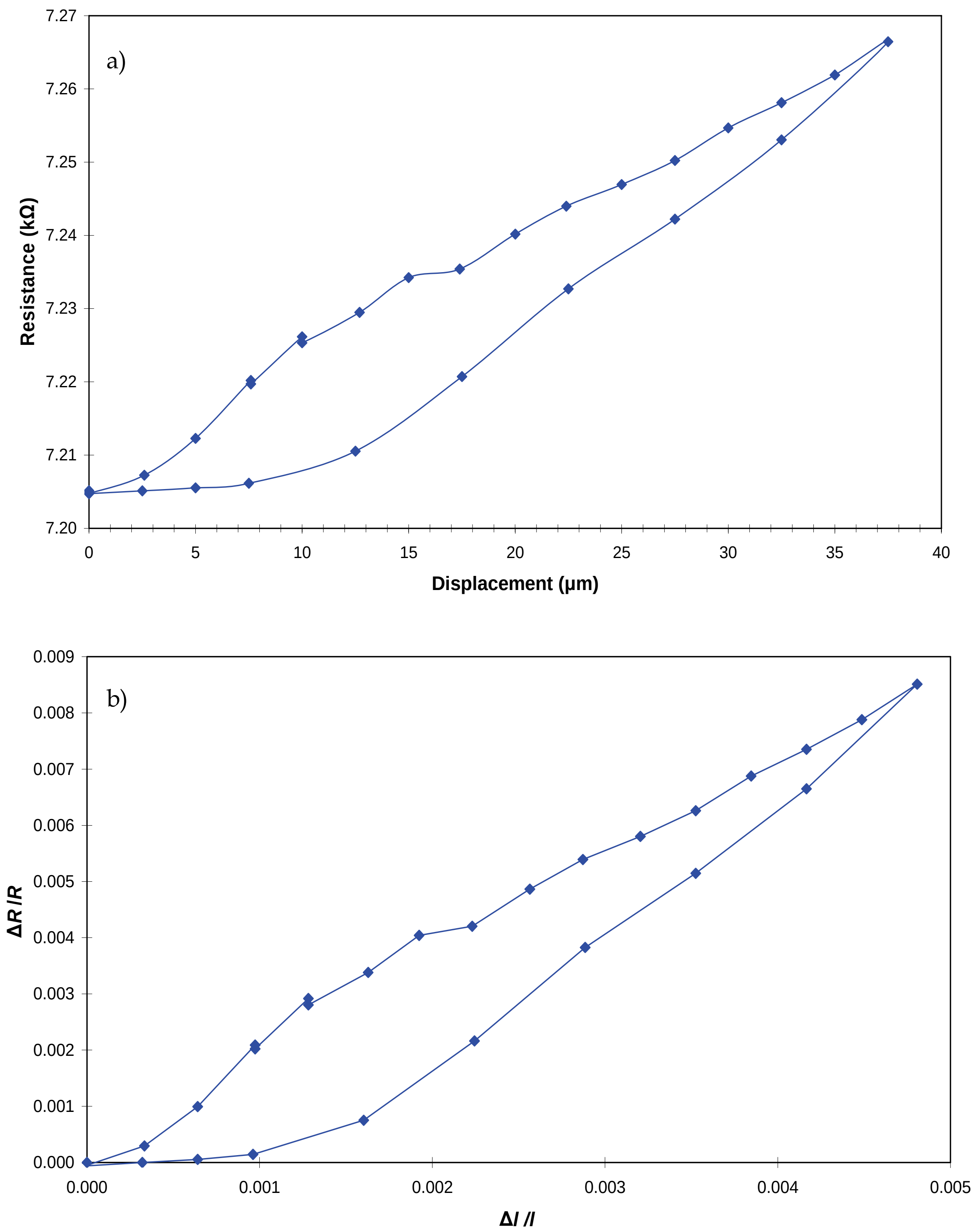

Figure 4: *a) Resistance as a function of load point displacement, for increasing (upper branch) and decreasing (lower branch) length, as measured on the Micro-Displacement Rig; b) Fractional change in resistance, ΔR/R, as a function of fractional change in length, Δl/l, based on data in a)*

A strain-gauge specific adhesive, M-Bond® AE epoxy resin combined with curing agent 15, was originally chosen for its mechanical properties after setting. Application of the AE-15 adhesive was successfully practiced on dummy gauges manufactured from copper. When applied to the silicon gauges, however, it was discovered that the adhesive does not remain within the load ring but spreads along the *entire* gauge structure through what is assumed to be a capillary action due to the silicon-aluminium contact. This flow occurs even with the AE-15 cured at room temperatures and below, rather than at the high temperatures > 50°C as recommended by the manufacturer. An alternative method will be investigated, such as the use of a higher viscosity epoxy (eg. Araldite 2014) or attaching a metal base to the contact surface of the load rings thereby breaking the Si-Al contact.

7.2 Irradiation

A programme of irradiations will be instituted following the characterisation of the SiSGs in the absence of radiation damage. The use of different radiation types will allow an inter-comparison between ionisation and displacement damage effects. The planned irradiation programme involves gamma and neutron exposures in the HPPD Radiological Exposure Laboratory, in conjunction with proton exposures provided by the Australian Nuclear Science and Technology Organisation (ANSTO). The Radiological Exposure Lab has a High-Intensity Gamma Calibrator facility that can be used to expose the devices to an intense Cs-137 gamma radiation environment, with control over the dose-rate. An americium-beryllium source of neutrons is also available for neutron exposures within the Lab.

ANSTO runs a dedicated particle accelerator facility – STAR, Small Tandem for Applied Research – for nuclear-based research. This facility is available for use by universities and research organisations such as DSTO, and can provide a steady beam of protons with a specified energy anywhere between 2 and 16 MeV. Irradiations are performed within an ultra-high vacuum. Samples are mounted on individual plates, 'sticklets', which are then bolted onto a long rod, the 'stick', whose lateral motion controls the placement of samples within the particle beam.

The beam consists of hydrogen ions accelerated to the required energy. As every hydrogen ion carries an electrical charge and a flow of electrical charge defines a current, the number of particles flowing per second is monitored as an electrical current (measured when the beam strikes an element known as a faraday cup). Magnets along the beamline provide focussing of the beam, allowing the beam diameter to be controlled. Combined with the beam current, the beam diameter provides control over the particle flux, the number of protons incident at the sample per cm^2 per second. An 8 mm beam-diameter was used in all irradiations to ensure full coverage over the entire ring structure.

A series of preliminary proton irradiations have been conducted at the STAR accelerator, with the aim of defining the methodology for work in the ANSTO facility and resolving any issues that might arise during the exposures. In the first instance a square-headed MEMS strain gauge was irradiated. Several irradiations were performed on the device,

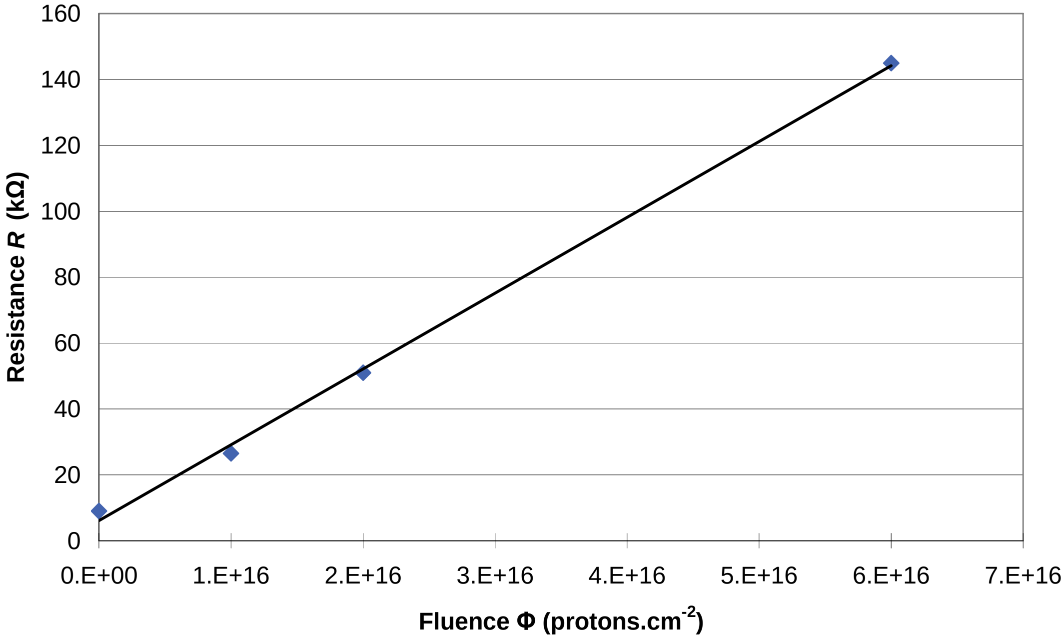

Figure 5: *Change in resistance with increasing proton exposure. The line is a guide to the eye.*

applying 3.5 MeV proton exposures at varying currents and exposure times to give different particle fluences Φ (protons.cm^{-2}).

A higher current provides larger numbers of ions per second, allowing higher particle fluences to be reached within a shorter time period. However, it was found that significantly high currents (of the order of 550 nA) destroyed the polyimide backing of the device. This resulted in a loss of electrical connectivity between the contact pads of the strain gauge and the electrical connectors of the polyimide flexi-circuit along one edge of the gauge. A moderate current of approximately 200 nA was determined to be appropriate for proton irradiations of the SiSGs.

Problems were also uncovered in the appropriate mounting, orientation and alignment of the devices. The majority of the initial exposures showed little changes to the resistances. When the high current exposure was applied, the resulting damage was offset from the centre of the strain gauge, leading to the realisation that the alignment was incorrect. The solution was to design and manufacture customised sticklet plates.

In addition to resolving these issues, a baseline for the radiation effects was established. After adjusting the alignment for the observed offset, the resistance of the measurable piezoresistor increased on average from 9.1 kΩ to 26.5 kΩ as a result of a total particle fluence of 1x 10^{16} protons.cm^{-2}.

A second series of irradiations was performed some time after the first, to verify the solutions devised in response to the issues previously identified. The customised sticklet plates, combined with an improvement by ANSTO in the video monitoring of the exposure chamber, allowed for much more precise device alignment. The original SiSG

irradiated previously was further exposed, out to a total cumulative fluence of 6 x 10^{16} protons.cm^{-2}, resulting in an increase in resistance to 145 kΩ. A second square-headed SiSG was also irradiated, to a total Φ = 2 x 10^{16} protons.cm^{-2}. The resistance increased from 9.5 kΩ to 50.7 kΩ. It is apparent from Figure 5 that resistance changes reasonably linearly with fluence above 1 x 10^{16} protons.cm^{-2}, with an average resistance change of approximately 20 kΩ per 1 x 10^{16} protons.cm^{-2}.

While an exposure of this scale is not expected within the normal operational parameters of the strain gauges, it is instructive to see the magnitude of the resistance change that results. If the degree of resistance change is equal across all resistors, as would be expected from a uniform exposure of a SiSG to radiation, then there will not be any observed change in the voltage output of a Wheatstone bridge circuit. A non-uniformity of accumulated radiation dose over the sensing piezoresistors, on the other hand, will result in resistance increases of differing magnitude and hence an apparent shift in output voltage. It is possible that this radiation-induced voltage shift may be misinterpreted as an apparent strain.

8. Conclusion

While there is limited literature on the radiation effects in MEMS devices or components, there are indications that some MEMS technologies exhibit vulnerability to radiation effects. Of particular interest are silicon strain gauges developed within DSTO for structural health monitoring of vehicle panels.

Two test methodologies to characterise the strain gauges have been developed; namely, direct control over the piezoresistor length changes, or application of strain with the devices mounted on a dogbone. Each of these methods has associated difficulties due to the particular design and extreme fragility of the silicon strain gauges. Solutions for overcoming these difficulties were proposed, involving modifications to the Micro-Displacement Rig and investigations of alternative adhesives or mounting. These solutions must be investigated before a complete electrical and mechanical characterisation of the silicon strain gauges may be reliably performed.

Following the electrical and mechanical characterisation, a series of irradiations is to be undertaken. This will involve exposures to gamma-rays and neutrons within the HPPD Radiological Exposure Laboratory as well as proton exposures in an accelerator facility at the Australian Nuclear Science and Technology Organisation (ANSTO). Preliminary proton irradiations have been performed to define the methodology for the exposures in the ANSTO facility. This early work has demonstrated almost linear change in resistance due to the radiation damage effects of a proton exposure. These induced changes could potentially lead to errors in the determination of strain under conditions where the radiation exposure is not uniform over the entire device.

Of greater significance, however, is how the radiation affects the measurement of a true strain. The interpretation of the strain gauge output depends upon knowledge of the linearity between $\Delta R/R$ and $\Delta l/l$. It is quite possible that this relationship will be altered by radiation damage. This would result in an incorrect estimation of panel strain from the strain gauge output and the possibility that a fatigued panel is kept in service due to this incorrect reading. The extent to which the radiation damage alters this response as well as the fatigue lifetime of the strain gauges themselves remains to be determined. Once the modifications to the Micro-Displacement Rig are engineered and the dogbone mounting is accomplished, these effects will be fully investigated.

The number of SiSGs currently in possession is limited and the possibility for acquiring further gauges at this point in time is constrained by the production plans of the US manufacturer. A batch of 100 devices could be ordered, but at a cost of over $10,000; smaller production numbers are not feasible for the manufacturer. It would be possible to piggyback off the production run for an order by another company, but it is uncertain when this may occur. The particular etching technology required to produce these devices is not presently available in Australia. At the time of publication there was discussion that the technology might be acquired by an Australia company within the next year or two, which would perhaps lead to improved availability and reduced costs.

This situation places tight restrictions on the testing of the engineering solutions discussed, which presents difficulties because of the extreme fragility of the devices. Work should not result in the destruction of many devices, or else insufficient numbers of gauges will remain for successful continuation with the next stages of the study. Four silicon strain gauges is the absolute minimum number of working devices required for a sufficient study involving, at the very least, a series of neutron and proton irradiations. A more complete study will require up to double this number. At present, there are just sufficient numbers to cover a complete investigation.

As an extension of this work, knowledge of the relationship between radiation damage and sensor output obtained through completion of this study could potentially lead to the development of novel radiation sensors. Once this relationship has been established, the silicon strain gauges may be assessed for this role or the physical principles discovered may be applied in a new configuration.

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19. ABSTRACT

Despite limited reporting in the open literature describing the effects of ionising radiation on MicroElectroMechanical System (MEMS) devices or components, there are indications that some MEMS technologies exhibit vulnerability to radiation effects. To begin to gain an understanding of the issues surrounding the susceptibility of MEMS technologies, an investigation into the effects of radiation damage on the electronic and the mechanical properties of a specific MEMS silicon strain gauge will be conducted. The methodology followed is outlined in this report.